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RESEARCH PAPER

Distribution and tensile strength of Hornbeam (*Carpinus betulus*) roots growing on slopes of Caspian Forests, Iran

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Abstract: Biomechanical characteristics of the root system of hornbeam (*Carpinus betulus*) were assessed by measuring Root Area Ratio (RAR) values and tensile strength of root specimens of eight hornbeam trees growing on hilly terrain of Northern Iran. RAR values of the roots were obtained using profile trenching method at soil depth of the top 0.1 m. In total 123 root specimens were analyzed for tensile strength. Results indicate that in general, RAR decreases with depth, following a power function. The RAR values in up and down slopes have no significant statistical differences. In most cases, the maximum RAR values were located in soil depth of the top 0.1 m, with maximum rooting depth at about 0.75 m. The minimum and maximum RAR values along the profiles were 0.004% and 6.431% for down slope and 0.004% and 3.995% for up slope, respectively. The number of roots in the up and down slope trenches was not significantly different. In the same manner as for RAR, number of roots distributing with depth was satisfactorily approximated a power function. The penetration depths of above 90 percent of the roots were at soil depths of 50 cm and 60 cm for up and down slopes, respectively. Results of Spearman's bivariate correlation showed no significant correlation between the RAR value with tree diameter and gradient of slope and number of roots. The mean value of root tensile strength was 31.51 ± 1.05 MPa and root tensile strength decreased with the increase in root diameter, following a power law equation. Using ANCOVA, we found intraspecies variation of tensile strength.

Keywords: biomechanical; Hornbeam; *Carpinus betulus*; root area ratio (RAR); root system; root tensile strength.

Introduction

Slope failure and shallow landslides are a serious problem in Caspian forests, where bare soils are vulnerable to failure during intensive rainstorms. Especially, next to the forest roads, where the trees have been clear cut, the slopes are very vulnerable to failure. Sometimes shallow landslides destroy the roads and cut off wood extraction process from the forests. Past experiences show that slopes under vegetation are more resistant against mass movements and water erosion (Gray and Leiser 1982). Roots affect properties of the soil, such as infiltration rate, aggregate stability, moisture content, shear strength and organic matter content, all of which control soil erosion rates to various degrees (Gray and Leiser 1982). Vegetation can influence the above-mentioned processes in various ways. In this study, the biomechanical characteristics of roots are investigated, as this is important for stabilizing slopes. One of the most important mechanical characteristics of the roots is that they are strong in tension and weak in compression. Soils, on the other hand, are strong in compression and weak in tension (Pollen 2007). A combined effect of soil and roots results in a reinforced soil. When shearing the soil, roots mobilize their tensile strength, whereby shear stresses that develop in the soil matrix are transferred to the root fibers via the tensile resistance of the roots (Ennos 1990). The magnitude of root reinforcement depends on morphological characteristics of the root system (e.g. root distribution with depth) and root tensile strengths (Greenway 1987). If the root system characteristics, which govern soil stabilization (root area ratio and root tensile strength), could be better identified, screening of suitable species for use on unstable slopes would be more efficient (Genet et al. 2005). Root Area Ratio (RAR) provides a measure of root density in the soil (Abernethy and Rutherfurd 2001). It is strongly influenced by the local soil and climate characteristics, and associated vegetation communities and randomness (Bischetti et al. 2005). Furthermore, as root contribution to soil shear resistance is in part dependent on the root tensile strength of the plant species involved, knowledge of a range of root-wood tensile strengths provides important information that is often required in root-soil assessment analysis, and can be useful when selecting plant species for erosion control (Watson and Marden 2004). Tensile strength is considered one of the most important factors governing soil stabilization and fixation, and has therefore been studied in great detail. Root tensile strength is important index for considering soil reinforcement, and it can affect plant anchorage (Genet et al. 2005). The slope is

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a complex environmental situation that can make plants to be subjected to a number of mechanical stresses, e.g. the turning moment induced by combination of slope and weight of stem and soil. In spite of the knowledge of biomechanics principles, and of the importance of vegetation in slope stability, the mechanical characteristics of the root system in plants growing on a slope have never been thoroughly investigated (Chiatante et al. 2003). Adaptive growth below ground may be even more important as a compensatory mechanism to self-loading, but there is only limited information on biomass allocation of roots (Canadell and Roda 1991; Nicoll and Ray 1996) within the structural root system of large forest trees (Coutts et al. 1999).

In mature trees, taproot's size eventually becomes insignificant compared with that of the upper lateral roots in broadleaved trees (Lyford 1980). The upper lateral roots frequently show an uneven distribution around the trunk base in direct response to a number of differences in the rooting environment, such as mechanical impedance (Quine et al. 1991) and nutrition, or indirectly to unidirectional dynamic loading such as wind (Stokes et al. 1995; 1997). Chiatante et al. (2003) suggested that when a plant grows on slope, its root architecture assumes a bilateral fan-shape disposition. Improvement of the knowledge on root development and formation is needed in order to understand the effects of forest practices, such as cultivation treatments, on the growth and later on the wind- or slope-stability of the crop (Coutts et al. 1990). Some aspects of the root system biomechanics have been studied for conifer trees such as *Pinus* and *Picea* genus (Stokes et al. 1995, 1997; Nicoll and Ray 1996), but the related information is poor for broadleaved tree species (Di Iorio et al. 2005). Although the role of roots in improving slope stability has long been recognized, the biomechanical characteristics of Caspian plant root systems have not been thoroughly studied yet.

The main objective of this study was to reveal biomechanical characteristics of undisturbed trees (seed origin) of hornbeam (*Carpinus betulus*) in slopes due to its widespread distribution in the Caspian forests. The species occupies more than 33% of standing volume of these forests. Amongst the 50 trees species in the Northern Iran, hornbeam is considered as a potential slope stabilizing plant. There is, however, no documentation on the contribution of this species in terms of slope stability enhancement in Iran.

Materials and methods

Site details

Hornbeam is a native species in Caspian forests and grows in mixed stands with oak and beech, and with iron wood in some areas. The species requires a warm climate for good growth, and occurs at elevations up to 1 000 m above the sea level. It is a medium to large-size tree reaching heights of 15–25 m, rarely 30 m. The study site was located in educational and experimental forest of University of Tehran in Northern Iran, on the middle part of the Caspian forests. The site itself was located on a west-facing slope at 350–550 m altitude (latitude 36°29´N and longitude 50°33´E). The weather is humid and mild, with a relatively limited range of temperature fluctuations. The average annual rainfall at this site is 1 350 mm, falling mostly as rain. The mean summer and winter temperatures are estimated to be 22.5°C and 10°C, respectively. The management for the Hornbeam forest is based on selection system and is followed to ensure sustainable development and yield. Ground skidding is used to transport logs from stands to depots, and then logs are loaded and extracted from forest by means of trucks. However, occurrence of shallow landslides sometimes halts the extraction of logs. In one occasion, occurrence of a landslide near road network destroyed the road and caused a delay in wood extraction for several months.

Selection of trees

Eight seed-origin trees (single stemmed), were randomly chosen from compartment number 104 for the root system analysis. It is well known that coppicing alters root decay (O'Loughlin and Watson 1979; Watson et al. 1999) and growth (Paukkonen and Kauppi 1998). In general, these alterations might hide the species-specific responses to mechanical stress. Only trees without neighbors in a radius of 2 m were selected for the study (Di Iorio et al. 2005). Their diameter at breast height (DBH) was measured and the gradient of the slope on which they were growing was recorded. Tree characteristics along with site conditions are summarized in Table 1.

Table 1. Tree characteristics, total number and maximum penetration depth of roots for each sample.

			Downslope		Upslope	
Sample	Slope (%)	DBH (cm)	Number	Depth (cm)	Number	Depth (cm)
C1	27.0	40.4	159	72	133	66
C2	30.5	43.0	133	63	128	61
C3	25.0	55.4	54	56	43	46
C4	26.5	32.5	64	68	62	48
C5	20.0	27.7	204	86	135	67
C6	25.0	28.7	87	72	76	50
C7	32.0	26.1	61	60	45	45
C8	32.0	40.4	42	68	54	60

Note: C1-C8 represents eight seed-origin trees (single stemmed) randomly chosen from compartment number 104 for the root system analysis. DBH, diameter at breast height.

Estimation of root area ratio (RAR)

Variation in root distribution can be assessed using the index of root area ratio (RAR), which has been defined as the ratio of the sum of the root areas to the area of soil profile of root intersecting (Wu et al. 1979; Gray and Leiser 1982). In order to obtain RAR values, a profile trenching method was used (Burke and Raynal 1994; Abernethy and Rutherfurd 2000; Schmid and Kazda 2001; Simon and Collison 2002; Bischetti et al. 2005; Greenwood et al. 2006; Sun et al. 2008). Around each sample tree, two trenches were excavated at a distance of one meter from the tree, one in the downslope and the other in the upslope direc-

tion, down to the maximum rooting depth. Trenches were excavated to expose a fresh profile of rooted soil. RAR values of all roots with a diameter larger than 0.1 mm were obtained at soil depth of 0.1 m (Mattia et al. 2005). Roots of diameter less than 0.1 mm were too difficult to recognize (Bischetti et al. 2005). Roots were assumed to be circular in cross-section. Root area was calculated by using the diameter of a circle with equal circumference (Di Iorio et al. 2005). The RAR distribution with soil depth was then determined. Then, the number (Normaniza et al. 2008), average diameter (Sun et al. 2008) and maximum depth of roots were measured in both upslope and downslope trenches.

Tensile strength tests

Roots for tensile tests were collected from forest stand in May 2008. Live roots were collected from soil besides trees at a depth of about 30 cm below the soil surface (Cofie and Koolen 2001). In order to prevent pre-stress effects, none of roots were pulled; instead they were cut with a sharp scissor. Finally, the roots were left to dry in the open air for about an hour (Mattia et al. 2005). Afterwards the root specimens were cut with a sharp scissor and stored in airtight plastic bags with a 15% alcoholic solution in order to prevent mould and microbial degradation (Bischetti et al. 2005; Mattia et al. 2005). Tensile tests were conducted on fresh roots within one week after sampling (Bischetti et al. 2005). In the laboratory, the roots were thoroughly inspected for possible breakage and peeling. Root hairs were carefully dismembered. Suitable root samples with a root length of about 150 mm were cut (Cofie and Koolen 2001). Before each experiment began, root diameter was obtained by measuring the diameters at five different positions along the length of the roots. Tensile strength testing was conducted using a computer controlled Instron Universal Testing Machine (SANTAM co. /SMT-5), equipped with a 500-kg maximum-capacity load cell. By visual inspection, root samples were positioned as vertical as possible with its axis coinciding with the load cell. The root ends were clamped and a strain rate of 10 mm/min (Bischetti et al. 2005; Pollen 2007) was applied until rupture occurred. The applied force required to break the root was taken as the measure of root strength. Tensile strength was calculated through dividing the applied force by the cross-sectional area of the root at its rupture point. Tests subject to slippage, or those roots that broke due to crushing at the jaw faces, were disregarded (Bischetti et al. 2005; Cofie and Koolen 2001).

Data analysis

Curve estimation was used to explore the function that exists between distribution of RAR and number of roots with depth. Correlations between number of roots and RAR values with DBH and gradient of slope were tested with Spearman's bivariate correlation coefficient. Paired samples T-test was used to compare depth and number of up- and downslope roots. In this study, the roots were collected from four trees, thus, the intraspecies variations of tensile strength can be assessed. To determine whether there were any differences in root strength in four hornbeam trees, the test results were subjected to analysis of covariance (Abernethy and Rutherfurd 2001). Setting the log-transformed root-strengths (Watson and Marden 2004) as the dependent variable and diameter as the covariate, we tested the null hypotheses that there was no significant difference in root strength due to different hornbeam trees (Intraspecies variations). Differences were only considered to be significantly different if P<0.05. All data were analyzed with SPSS15.0 statistical software.

Results

Root area ratio

RAR values showed a great variability with the changes of soil depth and location. In general, the average RAR decreased with soil depth except for the third and forth layers in up and down slopes. The RAR values in up and down slopes had no significant statistical differences (Fig. 1). In most cases, the maximum RAR values occurred at soil depth of the top 0.1 m, which the maximum depth is about 0.75 m. The minimum and maximum RAR values along the profiles were 0.004% and 6.431% for downslope and 0.004% and 3.995% for upslope, respectively. The decrease in RAR with depth was tested by some mathematical functions, where the power not only had a high R square but also had a low standard error of estimation (Fig. 2).

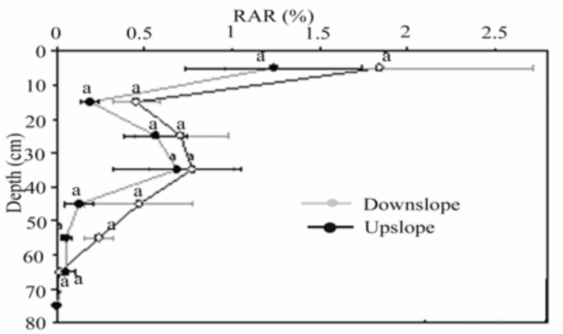

Fig. 1 Average RAR values for downslope (○) and upslope (●) (data are mean ± SE, n = 8. For each depth, means with same letter are not significantly different. (p > 0.05)). The site is located in educational and experimental forest of University of Tehran in Northern Iran, on the middle part of the Caspian forests.

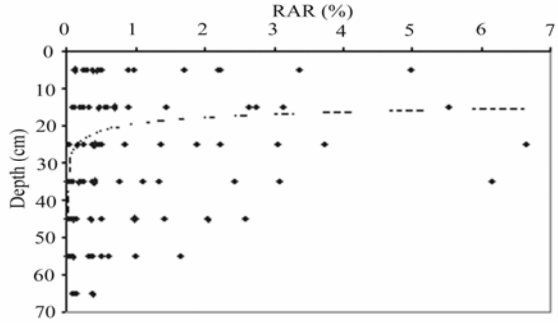

Fig. 2 Scatter plot for RAR values at different depths and fitted power function

Number and maximum penetration depth of roots

The average number of roots in each depth of up and down slopes had no statistical difference except for in the soil depths of 45 cm and 55 cm, where the number of roots in down slope was higher (Fig. 3). Total number and maximum depth of roots for each profile were summarized in Table 1. The results showed that the total number of roots in up and down slope trenches had no significant statistical differences.

No significant correlation was found between number of roots, RAR values with DBH and gradient of slope. But differences in root depth of up and down slopes were statistically significant and root depth for down slope was deeper than that of up slope and average depths were 68.12 cm and 55.37 cm, respectively. The reduction in the number of roots with depth was tested by some mathematical functions, where the power not only had a high R square but also had a low standard error of estimation (Fig. 4).

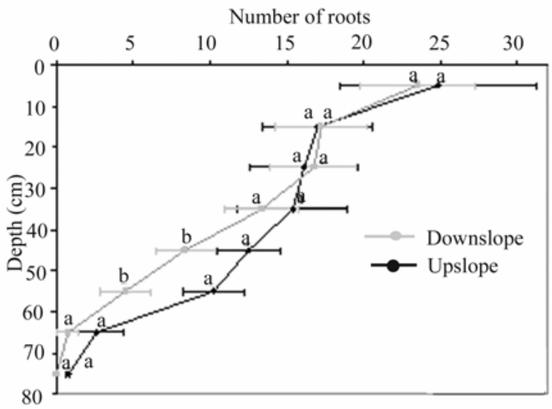

Fig. 3 Average number of roots for up and down slopes (data are mean ± SE, n = 8. For each depth, means with same letter are not significantly different ($p > 0.05$)). The site is located in educational and experimental forest of University of Tehran in Northern Iran, on the middle part of the Caspian forests.

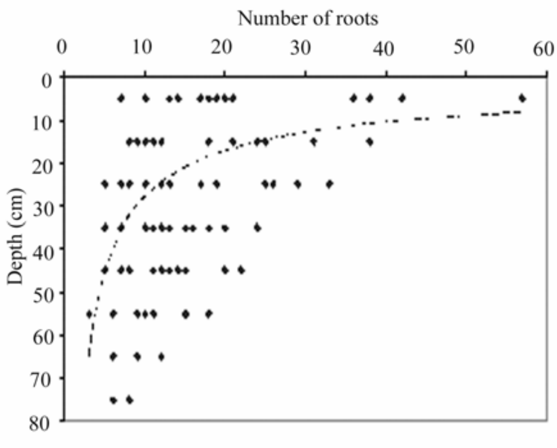

Fig. 4 Scatter plot for number of roots at different depths and fitted power function

Tensile strength tests

During the experimentations, root slippage within the clamping devices was associated with exertion of inadequate clamping force whilst failure of roots close to clamping devices was caused by application of large clamping forces. After a number of trial experiments, appropriate clamping force was developed by experience (Abernethy and Rutherfurd 2001). Stress–strain curves obtained by traction tests have been processed to obtain peak values of tensile strength (Bischetti et al. 2005). In total 123 root specimens were tested and analyzed. Results showed a great variability of measured root tensile strength among the specimens. The diameter of roots analyzed varied between 0.30 mm and 4.50 mm; the mean strength value was 31.51 ± 1.05 MPa and the maximum and minimum values recorded were 11.72 MPa and 62.20 MPa, respectively. Many authors (Abe and Iwamoto 1986; Bischetti et al. 2005; Gray and Sotir 1996) have demonstrated that root strength is strongly influenced by the root diameter. The results of root tensile strength must be analyzed in terms of strength-diameter relationship (Bischetti et al. 2005), therefore, the tensile strength data (T_r; MPa) versus root diameter (d; mm) has been corrected by fitting the power law. A power regression between tensile strength and diameter was significant for data set ($p < 0.001$). Mean root tensile strength was significantly different between trees ($F_{3, 122}$=5.807, p<0.001, ANCOVA) with regard to root diameter ($F_{1, 122}$=17.630, p<0.000, ANCOVA).

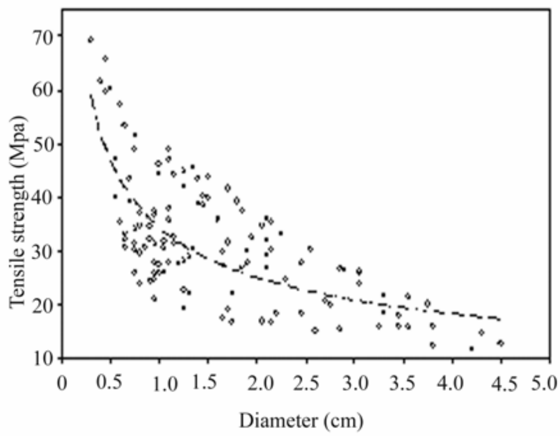

Fig. 5 Relationship between root tensile strength (TR) and root diameter (D) $y = 34.24x^{-0.45}$. The curve reveals increasing tensile strength with decreasing root diameter following power law ($R^2 = 0.52$).

Discussion

RAR is strongly influenced by both genetic and local soil and climate characteristics. However, generally RAR decreases with depth due to a decrease in nutrients and aeration and presence of more compacted soil layers (Bischetti et al. 2005). In the present study, the similar results were observed for RAR pattern, where the maximum RAR values were located in the upper soil of 0.1 m, and all samples had the variation of average RAR values with

depth, satisfactorily approximated by a power function. In this study, a high degree of variability was observed for RAR values. Bischetti et al. (2005) also reported that root density showed an extremely large spatial variability in both vertical and horizontal planes. Mattia et al. (2005) reported that since RAR values depend on species and their growing conditions, a high degree of variability is expected. On the other hand, Abernethy and Rutherfurd (2001) show that the RAR values are very susceptible to the effects of occasional larger roots, thus the scatter in the data has to be justified for this reason. Explanation of variability in the present results can also be attributed to inclusion of large-size roots. Watson and Marden (2004) stated that there was unlikely to be a general root architectural/morphological description or form for a particular plant species. Thus, they conclude that the above-mentioned parameters at one location are usually not transferable to another; therefore, they need to be examined at the local level. The RAR values obtained in this study were consistent with the results reported in other studies related to tree species in different environments dominated by hardwood forests (Morgan and Rickson 1995). In general, the decline of root density with depth below the soil surface is documented by several authors (Greenway 1987; Nilaweera 1994; Schmid and Kadza 2001; Shields and Gray 1993; Zhou et al. 1998). The RAR values of hornbeam are comparable with those determined for other deciduous trees (Greenway 1987; Schmidt et al. 2001). RAR distributions with depth were satisfactorily approximated by a power function with significant, high R^2 and low standard error of estimation (R^2 = 0.157; Std. Error of estimate = 0.765). Concerning other functions, Mattia et al. (2005) reported a logarithmic correlation between RAR and depth. Inconsistency in the results may be due to difference in the kind of plants. Mattia et al. (2005) investigated herbaceous and shrubs with relatively small sized roots, whereas the present study focused on tree species with large sized roots.

No significant correlation between the number of roots and gradient of slope is due to the low slope gradient (max slope = 17.7°). This may be justified by the results of Sun et al. (2008) that the anchorage resistances induced by the slope were dependent on slope gradients and significantly different for different slope classes. They referred slope gradients less than 25° as low. The present results show that root depth of down slope is deeper than that of up slope. This is consistent with the results of Di Iorio et al. (2005) and Marler and Discekici (1997). Chiatante et al., (2003) reported bilateral fan-shape disposition that roots on the downhill side of a slope could grow out from the soil, and in order to avoid death by desiccation the roots are obliged to change the growth direction, bending their apex back into the deeper soil layers or beneath the soil surface. Marler and Discekici (1997) also indicated that some lateral roots of papaya plants on the uphill side responded to the slope with negative gravireaction. In the same manner as for RAR, number of roots distributing with depth was satisfactorily approximated by a power function using an analytical approach, with significantly higher R square and lower standard error of the estimation (R^2 = 0.245; Std. Error of estimate = 0.512) in compared with other functions. Higher R square and lower standard error of estimation of number of roots versus RAR is due to omitted effect of larger roots. This is due to the fact that the effect of large or small roots in calculations of number of roots is the same but this is not the case for calculation RAR.

Simon and Collison (2002) suggest that a useful measure of root distribution is to calculate the depth above which 90 percent of all roots are found. They reported 38 cm and 56 cm depths for their investigated species. In the present study, penetration depths of the plant roots on up and down slopes were 50 cm and 60 cm, respectively. Thus, it can be concluded that penetration depth of roots in the present study is deeper than that studied by Simon and Collison (2002).

Results of the tensile testing of the roots were comparable to those of other woody species, in which a power equation existed between diameter and tensile strength (Bischetti et al. 2005; Genet et al. 2005; Gray and Sotir 1996; Mattia et al. 2005; Nilaweera 1994). The smallest roots were the most resistant in tension, and tensile strength increased with the decrease in root diameter, which is consistent with the results of Genet et al. (2005).

Tensile strength data presented in this study were compared with those for tree species (Greenway 1987). Tensile strength of hornbeam (31.51 ± 1.05 MPa) is similar to Alpine and Pre-alpine species including *Alnus incana* (32 MPa), *Pinus densiflora* (32 MPa), *Picea abies* (27 MPa), and *Quercus robur* (32 MPa). Also the results are comparable with the results of Watson and Marden (2004) that presented tensile strength of some common New Zealand species such as *Pittosporum tenuifolium* (29 MPa), *Pseudopanax arboreus* (28.16 MPa), *Knightia excelsa* (26.83 MPa), *Cordyline australis* (26.42 MPa), *Nothofagus solandri* (25.90 MPa) and *Pseudotsuga menziesii* (25.79 MPa).

In the present study, tensile strength of the plant root decreases with the increase in root diameter (Fig. 5), as found by many other authors, following a power law equation (Bischetti et al. 2005; Gray and Sotir 1996; Nilaweera 1994). These authors attributed this adverse relationship to the higher cellulose content in the finer roots. They observed that tensile strength increased with decreasing root diameter and with increasing cellulose content for *Pinus pinaster* and *Castanea sativa*. However, Genet et al. (2005) explained the adverse relationship as a result of differences in root structure.

Root tensile strength varies widely, both within and between trees. Genet et al. (2005) stated that "as root morphology is affected by local environment and since root chemical composition also varies with root morphology, it may be possible that the local environment also influenced root cellulose content". Thus, they suggested more studies on the differences in root tensile strength to be conducted on species from the same site. The results of the present study showed significant intraspecies differences in root tensile strength from a statistical viewpoint. To our knowledge, no other studies exit concerning statistical assessment of intraspecies variation of root tensile strength.

In conclusion, the presented data expand the knowledge on root area ratio and tensile strength of hornbeam on the hill slopes of Northern Iran. The results serve to expand understanding of the biomechanical characteristics of root systems of Caspian

species. This is a major issue in research, as the present lack of knowledge on the behavior of root systems of common tree species has become a limiting factor in using soil bioengineering techniques in forest environments (Chiaradia and Bischetti 2004; Bischetti et al. 2005).

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